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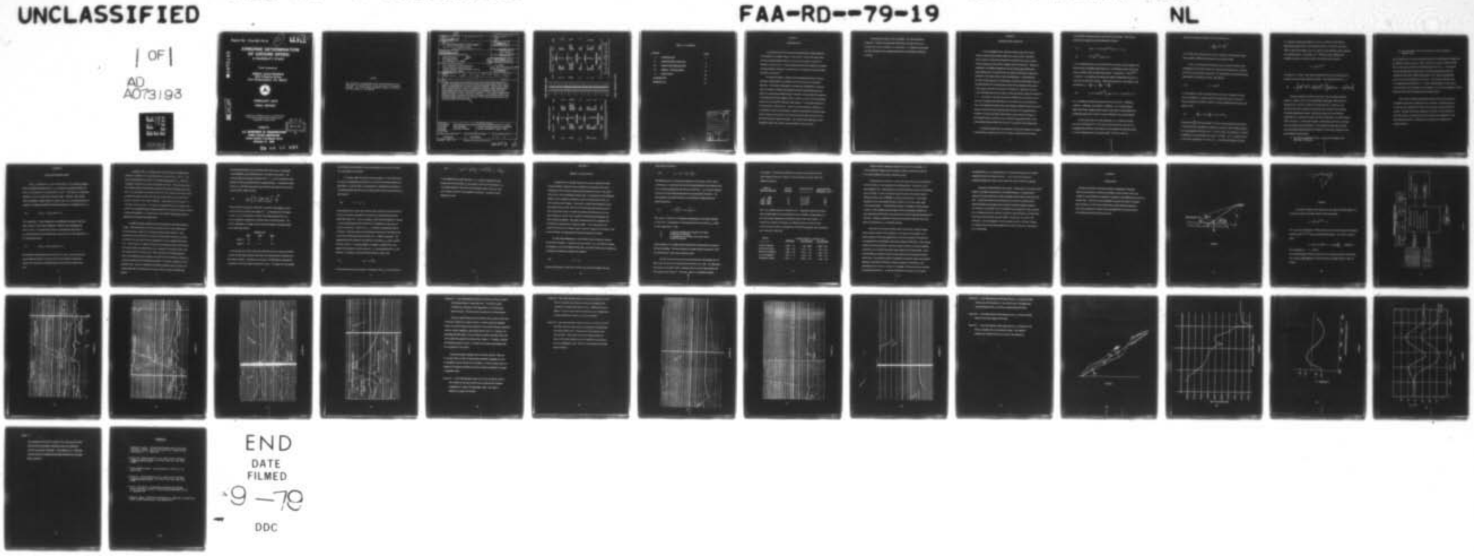

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# AIRBORNE DETERMINATION OF GROUND SPEED:

## A FEASIBILITY STUDY


Frank Greenwood

AMBAC ELECTRONICS
525 Virginia Drive
Fort Washington, PA 19034


FEBRUARY 1979

FINAL REPORT



Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.



Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

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Technical Report Documentation Page

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 18 FAA-RD-79-19 19 | | 11 |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| 6 Airborne Determination of Ground Speed: A Feasibility Study. | February 1979 |
| | 6. Performing Organization Code |
| | 8. Performing Organization Report No. 12 41p. |

| 7. Author(s) | |
|---|---|
| 10 Frank Greenwood | |

| 9. Performing Organization Name and Address | 10. Work Unit No. (TRAIS) |
|---|---|
| Ambac Electronics / New<br>525 Virginia Drive<br>Fort Washington, PA 19034 | 15 11. Contract or Grant No.<br>DOT-FA78WA-4214 |
| | 13. Type of Report and Period Covered |

| 12. Sponsoring Agency Name and Address | 9 |
|---|---|
| U.S. Department of Transportation<br>Federal Aviation Administration<br>Systems Research and Development Service<br>Washington, D.C. 20590 | Final Report<br>Sept. 28, 1978 to Mar. 28, 1979 |
| | 14. Sponsoring Agency Code<br>FAA/ARD-480 |

15. Supplementary Notes

9 Final rept. 28 Sep 78-28 Mar 79,

16. Abstract


→ To obtain the aircraft ground speed during Instrument Landing System approaches an algorithm is developed which utilizes the glide slope deviation signal and the rate of descent as determined from the radar or barometric altimeter. The accuracy of these inputs is determined from a study of all appropriate Federal Aviation Administration Flight Inspection Records and from examination of topographic maps of the areas beneath the flights for which records were available. It was found that irregularities in the glide slope, variations in the slope of the terrain, and rapid fluctuations in the barometric pressure associated with wind shear will all induce excessive errors in the value obtained for the ground speed.


| 17. Key Words | | 18. Distribution Statement |
|---|---|---|
| Ground Speed<br>Wind Shear<br>Air Speed<br>Glide Slope | Glide Slope Deviation Signal<br>Radar Altimeter<br>Barometric Altimeter | Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161. |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 41 | |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized



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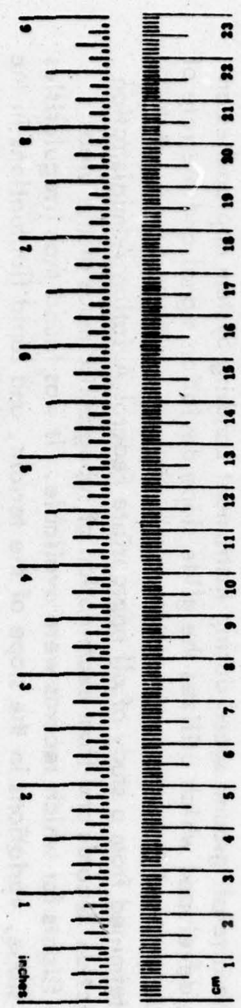
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

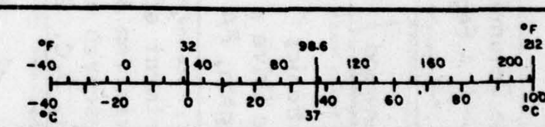
| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.




## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |




METRIC CONVERSION FACTORS

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# CHAPTER I

# INTRODUCTION

An aircraft flying at low altitude and airspeed during a landing approach is vulnerable to any sudden changes in wind velocity, which at best makes maintaining a controlled descent difficult, and at worst may result in a loss of lift sufficient to cause a crash. It has been determined that the availability of airspeed and ground speed to the pilot is a substantial aid in managing the craft under these conditions of wind shear.[1]

For economic reasons, a method of ground speed determination involving equipment already present on commercial aircraft was found to be a desirable objective. To this end an investigation was made into the possibility of using the radar or barometric altimeter derived descent rate plus the glide slope deviation signal to calculate ground speed during an Instrument Landing System (ILS) approach. All appropriate FAA Flight Inspection Data, consisting primarily of chart recordings produced by the Arma/FAA Automatic Flight Inspection System were obtained from the FAA offices in Oklahoma City. Data involving the barometric altimeter was unavailable for study, but meterological conditions associated with wind shear were found to impose serious doubts as to the value during wind shear encounters of any barometric altimeter based ground speed. Also, United States Geological Survey Topographic Maps were studied to assess the effects of slope of terrain.

To summarize the results of the investigation, the proposed method is inadequate. The effects of glide slope irregularities and slope of terrain are so adverse that further consideration is unwarranted. It is therefore recommended that other techniques of ground speed determination be identified, studied and evaluated.

# CHAPTER II

## GROUND SPEED ALGORITHM

A runway equipped with an instrument landing system gives vertical guidance along the proper descent angle to the correct runway "touchdown" point by means of a radio beam directed from the glide slope antenna outward along the approach course at about 3 degrees above the horizontal. The beam is modulated at two different frequencies, the equal signal region defining the proper descent path, and the deviation from equality indicating the angular displacement of the aircraft above or below the glide slope. A pilot making an instrument landing approach can determine by consulting his glide slope indicator the angle between the horizontal plane and his craft as measured at the antenna. If the average inclination of the center of that particular glide slope is given as $\theta$ and if the glide slope deviation signal is $\delta$ then the elevation angle will ideally be $\theta + \delta$. The antenna is typically located about 1000 feet from the approach end of the runway and offset 400 to 600 feet ($d_o$) to one side of the runway centerline. Thus a pilot approaching directly above the imaginary extended centerline and maintaining a constant (normally zero) glide slope deviation will be guided toward a touchdown on the runway abeam the glide slope antenna (point O in Figure 1). Upon approaching or crossing the runway threshold the geometrical effect of the antenna offset becomes evident and the use of $\delta$ for guidance must be abandoned.

It has been proposed that this knowledge of the aircraft's position with respect to the glide slope combined with the rate of descent as determined by the radar

(or barometric) altimeter be used to calculate the ground speed. The following relations exist among the quantities illustrated in Figure 1:

$$\tan\phi = (1 + (d_o/x)^2)^{1/2} \tan(\theta + \delta) = y/x \tag{1}$$

$$(x^2 + d_o^2)^{1/2} = y/\tan(\theta + \delta) \tag{2}$$

It must be emphasized that $y$ is the altitude of the craft above a plane tangent to the Earth's surface at the glide slope antenna and $x$ is the distance to the craft from the runway centerline abeam the glide slope antenna. The quantity $(1 + (d_o/x)^2)^{1/2}$ in equation 1 is not precisely one because the angle $\phi$ is referenced to the point O, rather than the base of the antenna. Differentiating equation 2 with respect to time and denoting $v_x = \frac{dx}{dt}$, $v_y = \frac{dy}{dt}$, $\dot{\delta} = \frac{d\delta}{dt}$:

$$v_x = (1 + (d_o/x)^2)^{1/2} \left(v_y/\tan(\theta + \delta) - y\dot{\delta}/\sin^2(\theta + \delta)\right) \tag{3}$$

If $d_o = 400$ feet the multiplicative factor has the value 1.02 for $x = 2000$ feet, 1.005 for $x = 4000$ feet, and 1.002 for $x = 6000$ feet. For a landing approach speed of 250 ft/sec, neglecting this correction would result in ground speed errors considerably greater than 5 ft/sec in the final 1000 feet to the runway threshold.

For the usual antenna array the glide slope is not a vertically oriented cone with a half-angle of $90 - \theta$ and vertex at the antenna base, but rather it is a hyperboloid of revolution having this cone as its asymptote and typically having a 1.5 foot closest approach to the antenna base[2]. To allow for this, the

square root in equation 3 should contain the additional term:

$$\left(\frac{1.5}{x \tan\theta}\right)^2 \approx \left(\frac{30}{x}\right)^2$$

For $x \geqq 1000$, that is for the aircraft not yet to threshold, this changes the square root by less than .0005 and this correction may be safely ignored.

Since $v_y$ will be obtained from either radar or barometric altitude, which are referenced to the Earth's surface and to mean sea level respectively, correction for the curvature of the Earth is required. For the distances concerned the following approximation is sufficiently accurate: (See Figure 2)

$$C = .88\ D^2 \qquad (4)$$

C is the correction in feet to be subtracted from the radar or barometric altitude, and D is the distance in nautical miles from the glide slope antenna to the craft. The error induced in the vertical velocity is found by differentiating the above with respect to time:

$$\frac{dC}{dt} = 1.76\ D\ \frac{dD}{dt} = 4.77 \times 10^{-8}\ x v_x \qquad (5)$$

The derivative $\frac{dD}{dt}$ is the ground speed in nautical miles per second and the constant in the second half of the expression arises from conversion to feet and feet per second. For a ground speed of 250 ft/sec and D = 4 nautical miles, the correction is .29 ft/sec corresponding to a ground speed error of about 5.5 ft/sec. For D = 1 nautical mile it is .07 ft/sec corresponding to 1.4 ft/sec in $v_x$. Both this and the factor involving

$d_o$ in equation 3 require knowledge of x, which is available from the Distance Measuring Equipment (DME). Even though the DME is not sufficiently accurate to derive a useful ground speed, using it for position in these relatively small corrections gives adequate results. For example, at x = 2000 feet or about 1000 feet from threshold, assuming x is correct to within .02 nautical miles, the error in:

$$(1 + (d_o/x)^2)^{1/2}$$

is limited to .3 % or less. Thus, several complications which cause relatively minor systematic errors have been noted and corrected. The complete equation for $v_x$ is:

$$(6) \qquad v_x = \left[ 1/\sqrt{1 + (d_o/x)^2} + \frac{4.77 \times 10^{-8}}{\tan(\theta + \delta)} \times \right] \left[ \frac{v_y}{\tan(\theta + \delta)} - \frac{y\dot{\delta}}{\sin^2(\theta + \delta)} \right]$$

The data available for analysis is the output of the Arma Flight Inspection System for a series of ILS-3 runs on three different glide slopes, RGR and OKC in Oklahoma City, and PVO at Atlantic City (See Figure 3).[3] In these runs, the test aircraft flew down the glide path producing time correlated trace recordings of the glide slope deviation signal, the localizer signal and of the altitude as determined by an inertial sensing system and also as determined by the radar altimeter. Further, for every .1 nautical mile traveled, as determined by the INS, an indicator mark was placed on the trace (Figure 4). The usefulness of these marks is limited to giving the approximate distance from threshold to aircraft and a rough idea of the ground speed for several reasons:

1) The marks are produced for every .1 nautical mile traveled or only about every 2.5 seconds.

2) The visual clarity of the traces precludes accurate conversions to numerical data.

For the Atlantic City runs a time correlated tabulation of aircraft position as determined by theodolite tracking was also provided, usually from a range of 15,000 or 25,000 feet in to the runway and several thousand feet down the runway. At half second intervals the glide slope deviation signal and inertial sensing system data were recorded and later used to determine the position of the center of the glide path beam at the aircraft's distance from the runway. This was then combined to give an average glide slope elevation ( $\theta$ ). A plot of the displacement of the center of the actual beam from the average was then produced ( $\delta_s$ ), with the independent variable being the time at which the measurement was made (Figure 5).

The localizer and glide slope deviation signal on the real time Arma plot are useable to about four nautical miles, but in all cases the altitude traces go off the chart about 4000 feet from the end of the runway or at about 250 feet of altitude. The glide path profile, presented as a function of time of observation rather than position, extends from the time of crossing runway theshold to a time about 100 seconds earlier, corresponding to the region from threshold to four nautical miles out.

# CHAPTER III

## GLIDE SLOPE IRREGULARITIES

Since $v_y$ is derived from y and $\delta$ is derived from $\dot{\delta}$, it is in general necessary when calculating the probable error in $v_x$ to consider the correlation between the error in y and the error in $v_y$ and the same for $\delta$ and $\dot{\delta}$. This results in a complicated expression, which only obscures the arguments made. Therefore, when altitude data is considered, a perfect descent is assumed, that is $\dot{\delta} = 0$, and the second term in equation 3 is neglected yielding the following expression for the probable error in $v_x$:

$$(6) \qquad PE\,(v_x) = PE\,(v_y)/\tan\,(\theta + \delta)$$

This is reasonable. If the altitude data is not sufficiently accurate for other wise ideal conditions it will never be adequate. Similarly, when considering the error in $\delta$ and $\dot{\delta}$, it is obvious that an error in $\delta$ has relatively little impact on $v_x$, because normally $\delta$ is much smaller than $\theta$ and occurs only in the combination $\theta + \delta$. To a good approximation:

$$(7) \qquad PE\,(v_x) = PE\,(\dot{\delta})\,y/\sin^2\,(\theta + \delta)$$

Thus attention is directed primarily to the errors in $\dot{\delta}$ and $v_y$, and it turns out that the most essential problem is not the accuracy of the altimeter or glide slope receiver, but the quality of the glide slope and the nature of the terrain flown over.

According to the U.S. Standard Flight Inspection Manual the glide slope elevation or alignment ( $\theta$ ) may be permitted to vary as much as $\pm$ .22° or $\pm$ 7.5% from its commissioned value, which if a standard landing speed of $v_x$ = 250 ft/sec is assumed, could result in an error on the order of 19 ft/sec. The obvious solution is more frequent checks of the elevation angle and making the most recent value available. For a glide slope over flat terrain like PVO, the variation would be due mostly to seasonal fluctuations in the water table and several checks a year could reduce the error to less than .05° or about 4 feet/sec. Other sites are not as fortunate. A 4 foot snow cover can cause a .4° change in average elevation and an antenna used at New York's LaGuardia Airport designed specifically to minimize the effect of terrain variations still exhibits a .1° variation due to 5 foot tides.[4] These represent ground speed errors of 33 and 8 ft/sec respectively.

Consider the traces of glide path structure produced by the Flight Inspection System. The test procedure involves visual position fixes at runway threshold and at the far end plus a vertical fix at threshold using the radio altimeter. These potentially contain sufficient error to cause the structure plot to deviate noticeably but smoothly from zero near the time corresponding to runway threshold (See Figure 5-C). This of course is in addition to the structure associated with the facility itself. In the region farther out substantial structure is apparent in the RGR and OKC plots and a lesser amount in the PVO plot. While well within the allowed guidelines (±20 micro-amperes) the amount present at the RGR and OKC facilities is sufficient to cause serious errors in the calculated ground speed. To see this, suppose that a pilot descends to the runway in a straight line elevated at precisely the same angle as the average glide path and intersecting the runway at the point abeam the glide slope antenna.

His glide slope deviation receiver should ideally indicate zero, with perhaps a small deflection near threshold because of the offset of the antenna. This is not the case since the signal received will be $-\delta_s$, that is the negative of the deviation of the actual glide path from average alignment. To estimate the effect of this on $v_x$, the following quantity was calculated using typical structure plots for each of PVO, RGR, and OKC.

$$(8) \qquad \frac{1}{t_2 - t_1}\left\{\int_{t_1}^{t_2}\left(\frac{\dot{\delta}_s(t)\, y(t)}{\sin^2(\theta + \delta(t))}\right)^2 dt\right\}^{1/2}$$

The time intervals correspond to 3500 feet to 2 nautical miles (Region A) and 2 nautical miles to 4 nautical miles (Region B). $\dot{\delta}_s$ is the derivative with respect to time of $\delta_s$ and its calculation involved a low-order polynomial fit to $\delta_s$, which considerably smoothed any of the short term (1-2 sec) fluctuations. The quantity represents an "average" value of the error induced in the ground speed due to glide slope "bends".

ERROR (ft/sec)

| | OKC | PVO | RGR |
|---|---|---|---|
| Region A | 38 | 5 | 17 |
| Region B | 43 | 4 | 20 |

As can be seen from various traces, the glide slope structure is usually oscillatory in nature with decreasing (angular) amplitude and increasing period as distance from the antenna increases. At distances on the order of 10,000 feet from threshold the contribution can be quite large and relatively constant. For Figure 5-B, the average

ground speed error produced by the structure between points I and II is 16 ft/sec for a time interval of 15 seconds.

In a realistic flight the received glide slope signal ( $\delta$ ) will be the sum of two parts, one representing the deviation of the craft from the ideal straight line glide slope ( $\delta_t$) and the other, as discussed above, representing the deviation of this idealized glide slope from the null reading points of the actual glide slope ($-\delta_s$) (See Figure 6).

$$\delta = \delta_t - \delta_s \tag{10}$$

Glide slope deviation traces under turbulent flight conditions will have deviations from zero with period comparable to or smaller than the glide slope structure's period (See Figure 4-C). Thus an averaging or other smoothing algorithm to remove $\delta_s$ from the glide slope deviation signal will be unsatisfactory under many not unusual circumstances. Unlike $\dot{\delta}$ and $v_y$, $v_x$ is affected comparatively little by turbulence or other excursions from the glide path due mainly to the inertia of the aircraft and its flight being nearly parallel ($\cos\theta = .9986$) to the ground. This suggests attention be directed to the possibility of smoothing $v_x$, which is usually relatively constant. If the ground speed is averaged or smoothed over a time greater than the period of the fluctuations of $\delta_s$, the associated error in $v_x$ will diminish. For example, if the form of the fluctuation is taken to be:

$$f(t) = \sin \frac{2\pi}{T} t \tag{11}$$

and the smoothing procedure is simply to average over time $T_A$, the result will be:

$$(12) \qquad f_{av}(t) = \frac{T}{2\pi T_A}\left(1-\cos\frac{2\pi T_A}{T}\right) \leq \frac{T}{\pi T_A}$$

In the unrealistically simple case when $v_x$ is a constant averaging will work because one can always take $T_A$ large enough to eliminate the error due to $\delta_s$. The question becomes: When the true ground speed varies in time, how much of its variation is lost for various degrees of smoothing? Discussion of this is deferred until later.

# CHAPTER IV

## TERRAIN - INDUCED ERROR

Altitude data from the radar altimeter was usually available from about 20 seconds before crossing the runway threshold to the stop end of the runway. Comparing it with the inertial guidance derived altitude and also, in the case of Atlantic City, with the theodolite tracking data, it was apparent that the difference between the two altitudes was basically a slowly varying function of time, but with occasional rapid changes. Unfortunately, United States Geological Survey maps indicate that for RGR, OKC and PVO the land beneath the glide paths for which radar altitude data is available lies almost entirely between two contour levels differing by ten feet and no correlation between general topography and radar altitude was possible. The sudden changes were found to correspond well with features on the map such as roads and creeks. Part of the traces in the Atlantic City data was of a highly irregular nature and judging from its relation to the known landmarks, was measuring the altitude from high grass or bushes.

Any short period abberations in radar altimetry data can be easily removed by some form of filtering. The slower variations however, are a very difficult problem. For example, in much of the RGR and OKC data, the inertial altitude trace is essentially a straight line indicating a constant rate of descent:

$$h_i = v_y t \tag{13}$$

The radar data however, often shows variation that conforms reasonably well over

some interval to the form:

$$h_r = v_y t + A\cos \frac{2\pi}{T} t \tag{14}$$

The additional term is of course the consequence of flying over a hill or valley. In the above, h is the distance the aircraft has descended below some arbitrary level and t is the time elapsed since the craft was at that level. $V_y$ is the rate of descent and A and T are the amplitude and period of the parametrized undulation. The error induced in the vertical velocity can be obtained by differentiating the second term giving:

$$- \frac{A\,2\pi}{T} \sin \frac{2\pi}{T} t \tag{15}$$

The values A = 4 feet and T = 10 seconds are appropriate for the region indicated on Figure 4-B. From equation 3, the consequences of this are errors in $v_x$, which can be catagorized in 3 ways:

1) A maximum instaneous error as great as 47 ft/sec
2) An RMS error of 33 ft/sec
3) An average error of 29 ft/sec over a time interval as great as 5 seconds

Similar examples with a slightly smaller magnitude but longer period can be seen in the flight recordings. The above example was chosen because the proximity of the two altitude traces makes visual comparison easier.

That this much error occurs over land whose elevation falls between two 10 feet contours is indicative of the difficulties that terrain can cause. As further proof the survey map was used to make a complete profile of the land directly below the OKC approach path (Figure 7). Obviously, there is a considerable variation

in the slope. To illustrate, consider the following four intervals for which the terrain slope and the error it induces in the ground speed (assuming a 250 ft/sec approach) are given:

| INTERVAL (feet from threshold) | LENGTH (seconds) | AVERAGE SLOPE | SLOPE-INDUCED ERROR IN $V_x$ (ft/sec) |
|---|---|---|---|
| 0 - 3500 | 14 | $-2.9 \times 10^{-4}$ | + 1 |
| 3500 - 12500 | 36 | $-4.2 \times 10^{-3}$ | +20 |
| 12500 - 16000 | 14 | $-1. \times 10^{-2}$ | +54 |
| 16000 - 20000 | 16 | $+5.0 \times 10^{-4}$ | - 2 |

This is not a problem peculiar to Oklahoma City. Topographic profiles of the terrain under the glide slope for the first 2500 feet out from threshold, average slopes, and the velocity errors induced were tabulated for several other major airports. To illustrate the variability of the slope, the 2500 foot interval was then divided in half and the calculation was repeated for both 1250 foot segments, each representing about 5 seconds of flight time.

| AIRPORT | AVERAGE SLOPE/ $V_x$ ERROR (ft/sec) (2500 feet) | (first 1250 feet) | (last 1250 feet) |
|---|---|---|---|
| Greater Pittsburgh | +.004 / - 19 | . 08 / +380 | +.088 / -418 |
| Dallas (Love Field) | +.002 / - 10 | -.016 / + 76 | +. 02 / - 95 |
| Baltimore (Friendship) | -.026 / +124 | -.016 / + 76 | -.036 / +171 |
| St. Louis (Lambert) | -.001 / + 5 | -.010 / + 46 | +.007 / - 34 |
| Washington (Dulles) | +.001 / - 4 | +.007 / - 34 | -.006 / + 27 |

Clearly the above represents a degree of error which is intolerable. As with the glide path irregularities the question of possible mathematical treatment of $v_x$ data to supress the incorrect contributions arises.

Unfortunately, the variation in time of the correct and incorrect contributions is often so similar as to be mathematically indistinguishable. Examination of the Arma Inspection Data glide slope structure traces confirms the existance of oscillations nearly sinusoidal in nature with periods ranging from about 30 seconds of flight or 7500 feet spatially down to 1000 feet or 4 seconds (See Figure 8). United States Geological Survey maps exhibit the same variations, with an even wider range in time scales possible. A simulated flight through a thunderstorm outflow produces variations in both airspeed and ground speed, which are strikingly sinusoidal with large amplitude (over 30 ft/sec) and a period of about 20 to 40 seconds (See Figure 9).[5] Obviously, to devise an algorithm to remove the unwanted contributions would also destroy the usefulness of $v_x$ in the above situation.

Examination of the terrain profiles makes it obvious that no simple average slope of terrain correction will be effective, but rather only the storage in an on board computer of fairly close approximation of the actual profile will be sufficient. Even supposing this were feasible, there remain substantial difficulties. Every landing would involve taking a position fix several miles out and then a continuous updating of position, so as to extract the correct terrain slope from the stored profile. Visual fixes are often not available; using the outer marker would involve several hundred feet of error. Calculating the point of interception of the glide slope using the beam's geometry and the plane's altitude is unreliable because of uncertainties in the glide slope and it's structure and lack of knowledge of the elevation above the plane of the glide slope antenna. To then use the somewhat inacurate fix and integrate

the determination of $v_x$ to update position is an algorithm whose errors can increase dramatically under very simple conditions. In fact if the terrain slope ever equalled the glide path angle for some interval the method would fail completely.

Barometric altitude probably is more useful. Unfortunately, its accuracy and the degree of the problem associated with the delayed response to changing descent rates cannot be evaluated since no flight recordings with barometric traces were available. It should be pointed out that during typical wind shear conditions ground based barometers have recorded rates of change in barometric pressure as great as two millibars in 15 minutes.[6] If this is attributed to the movement of a cold air outflow from a thunderstorm past the measuring instrument at about 20 knots, an aircraft flying at 140 knots could encounter the same change in 1/8 the time, or a rate of .018 millibar/sec, which corresponds to a ficticious descent rate of .50 ft/sec, yielding an average weather induced ground speed error of about 10 ft/sec for a time interval of over 100 seconds.

# CHAPTER V

## CONCLUSION

Erroneous contributions to the ground speed by irregularities in the glide slope and natural terrain variations have profiles in time so similar to the actual variations in ground speed that mathematical treatment cannot effectively discriminate between them. The size of the errors depends of course on the nature of the glide slope and terrain, but from what has been seen, a quite conservative estimate is that a typical approach will likely have ground speed errors of at least 10 ft/sec due to glide slope and 40 ft/sec due to terrain.

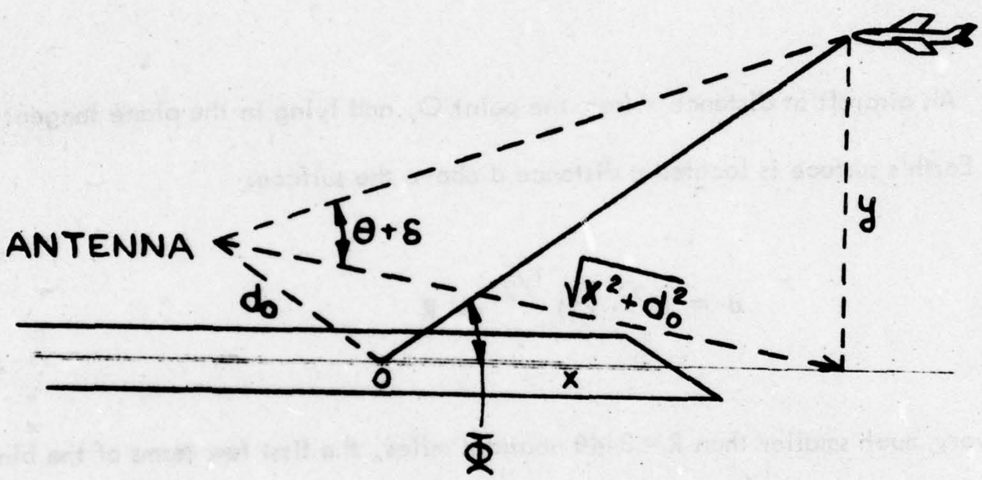



FIGURE 1

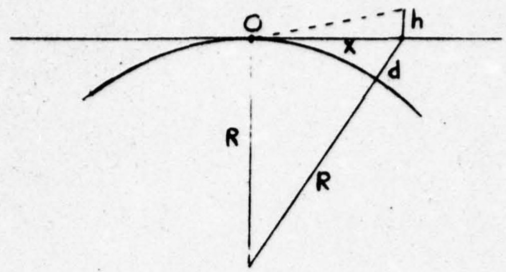



FIGURE 2

An aircraft at distance x from the point O, and lying in the plane tangent at O to the Earth's surface is located a distance d above the surface:

$$d = (R^2 + x^2)^{1/2} - R$$

For x very much smaller than R = 3440 nautical miles, the first few terms of the binomial expansion of $(R^2 + x^2)^{1/2}$ give an excellent approximation. For x and d in nautical miles:

$$d = R(1 + 1/2\,(x/R)^2 + \cdots) - R \approx \frac{x^2}{2R} = .000145\,x^2$$

For d in feet this is: $d = .833\,x^2$

For x small compared to R the two radii shown are very nearly parallel, and the correction d may be added algebraicly to the height above the tangent plane h to get the altitude.

**COMPUTERIZED FLIGHT INSPECTION SYSTEM**

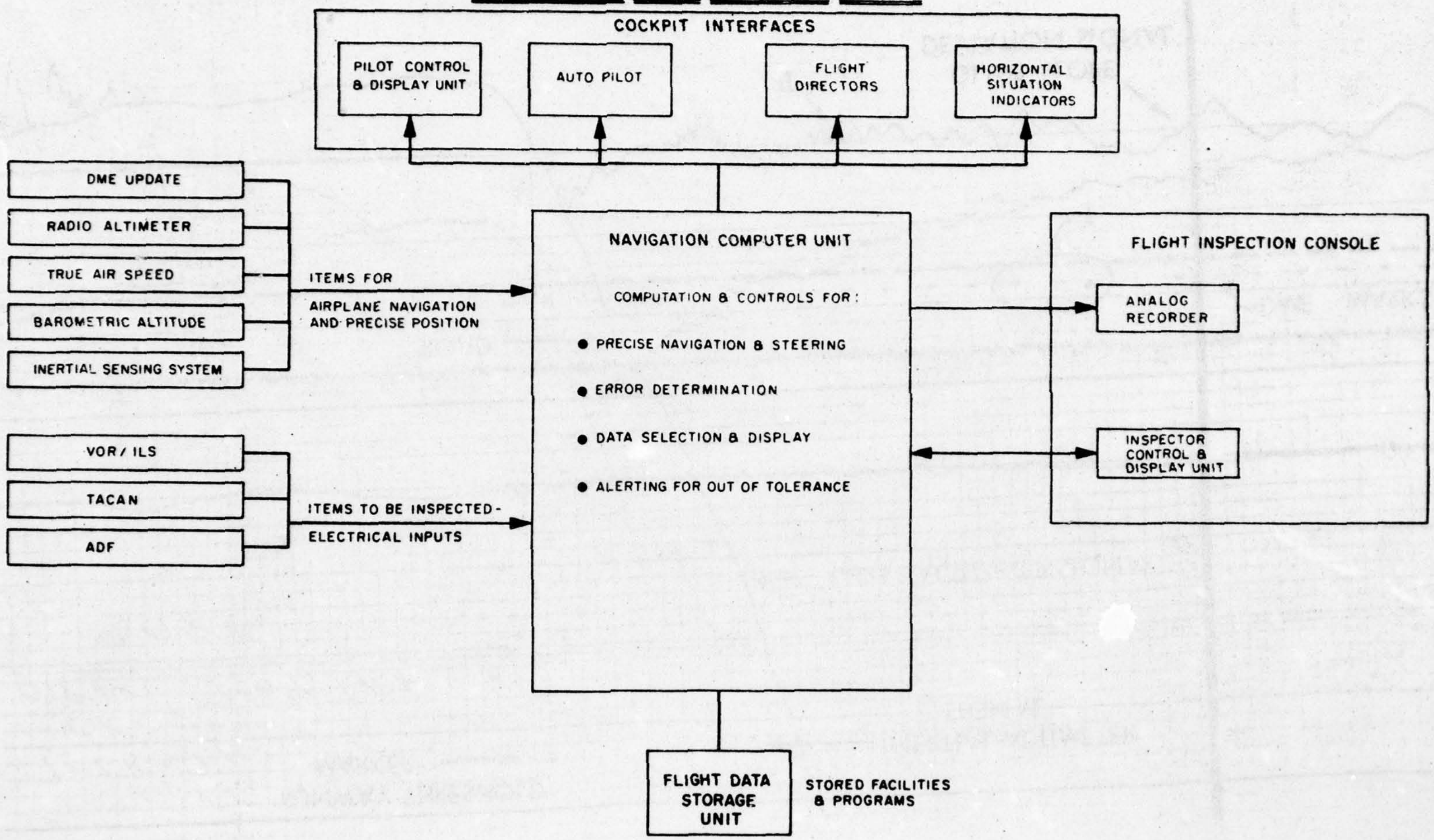



Figure 3

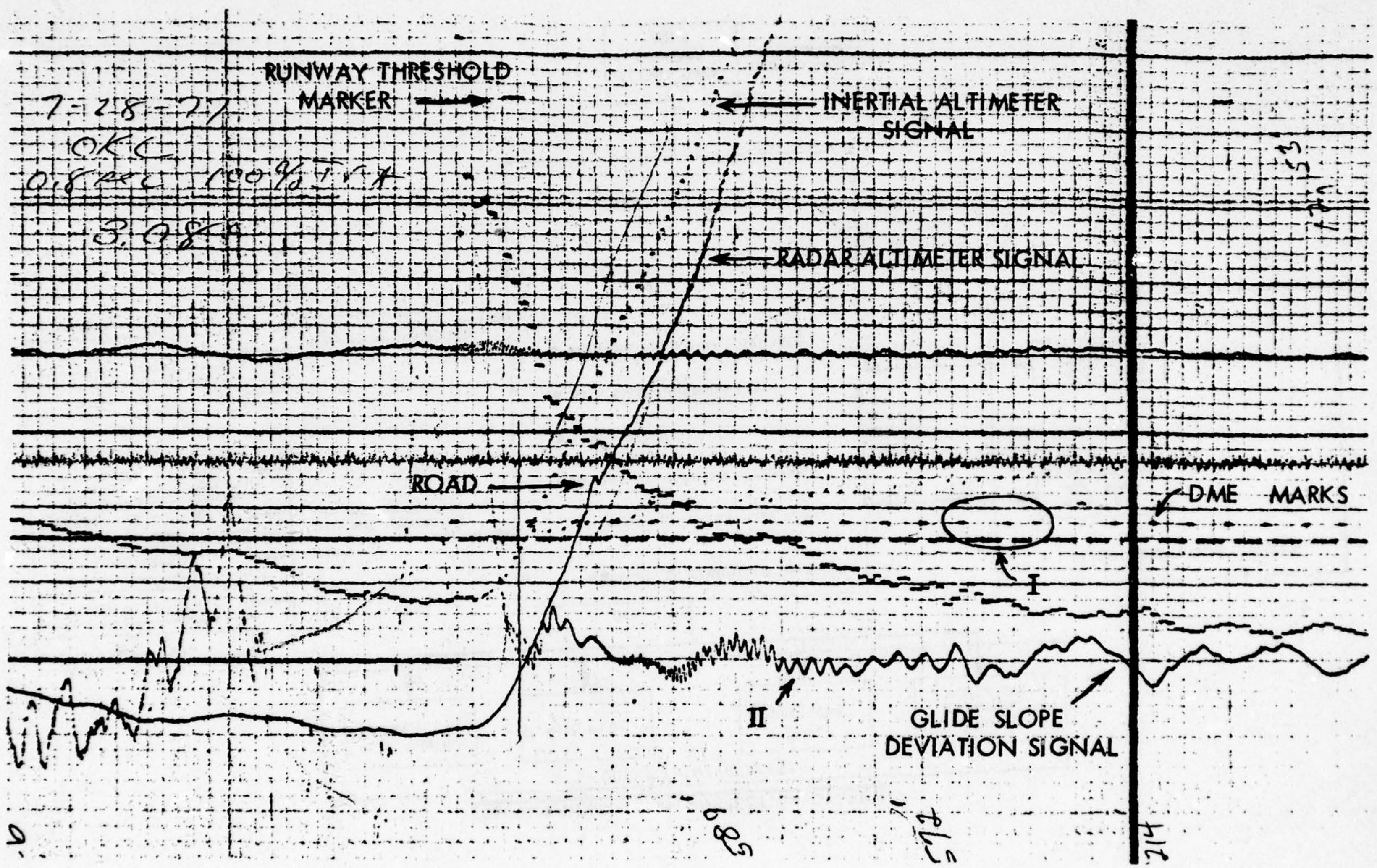
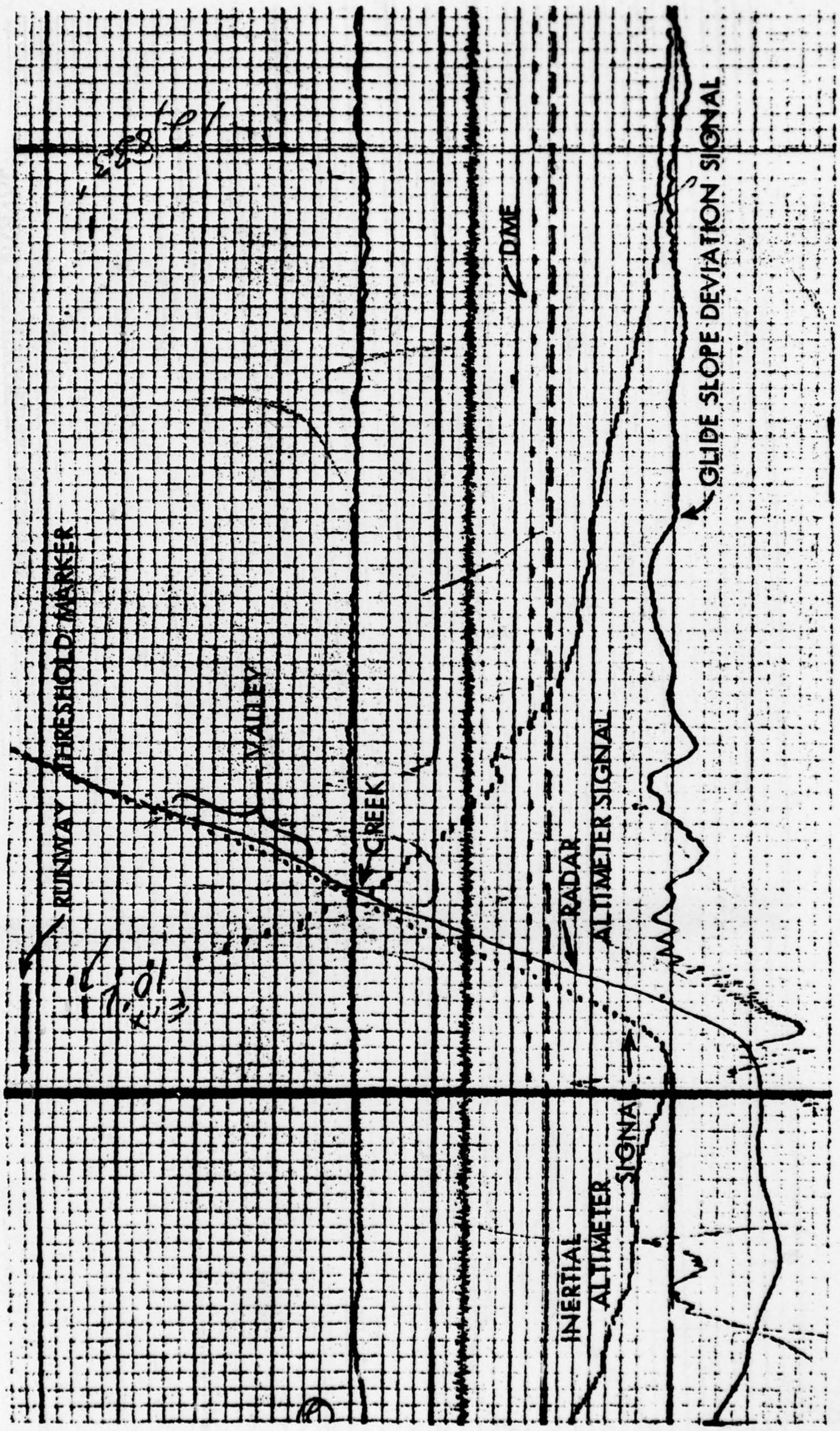

RUNWAY THRESHOLD MARKER
INERTIAL ALTIMETER SIGNAL
RADAR ALTIMETER SIGNAL
ROAD
DME MARKS
I
II
GLIDE SLOPE DEVIATION SIGNAL
7-28-77
OKC
3.0°

FIGURE 4-A



RUNWAY THRESHOLD MARKER
VALLEY
CREEK
DME
RADAR ALTIMETER SIGNAL
INERTIAL ALTIMETER SIGNAL
GLIDE SLOPE DEVIATION SIGNAL


FIGURE 4-B

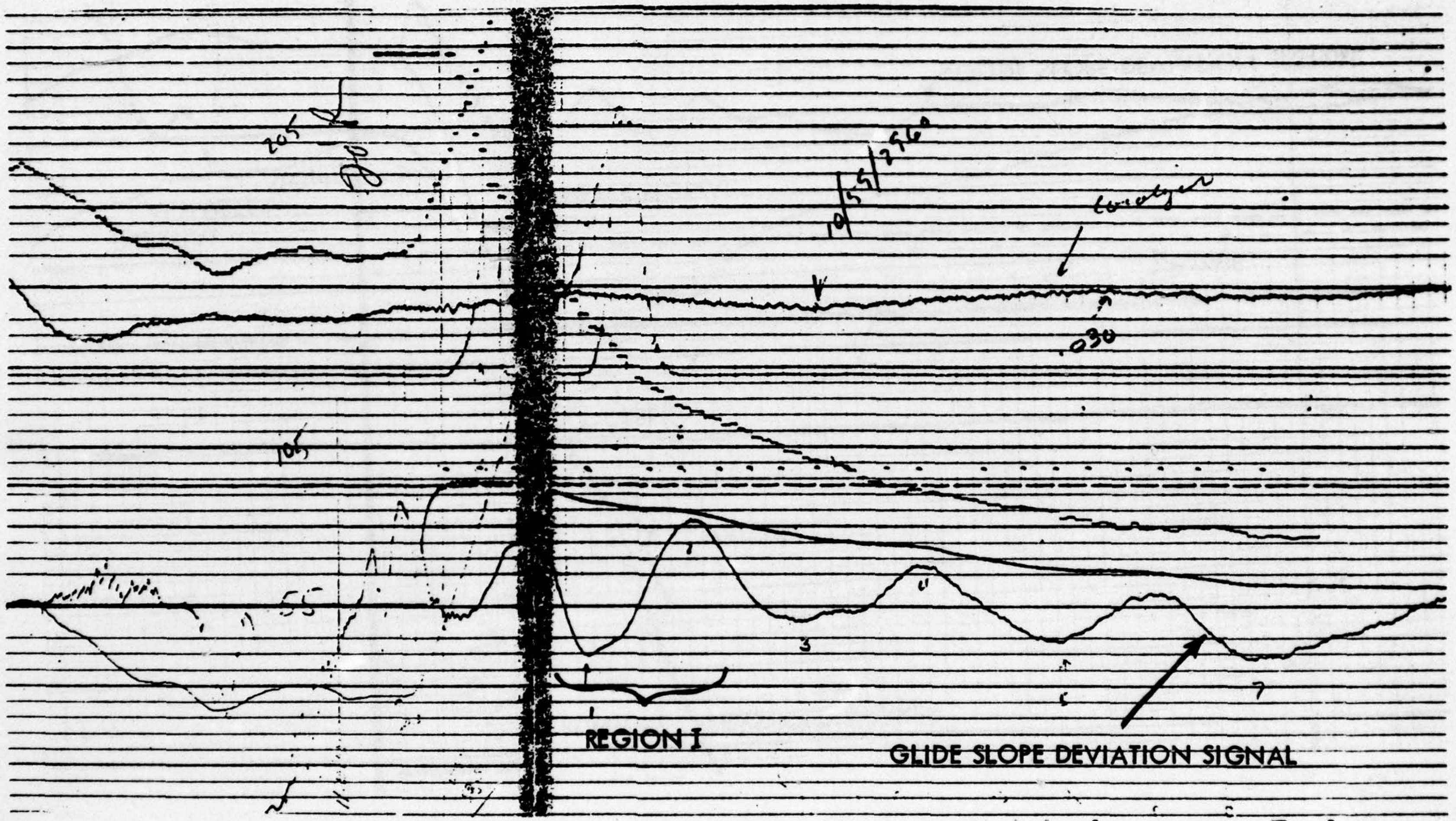



FIGURE 4-C

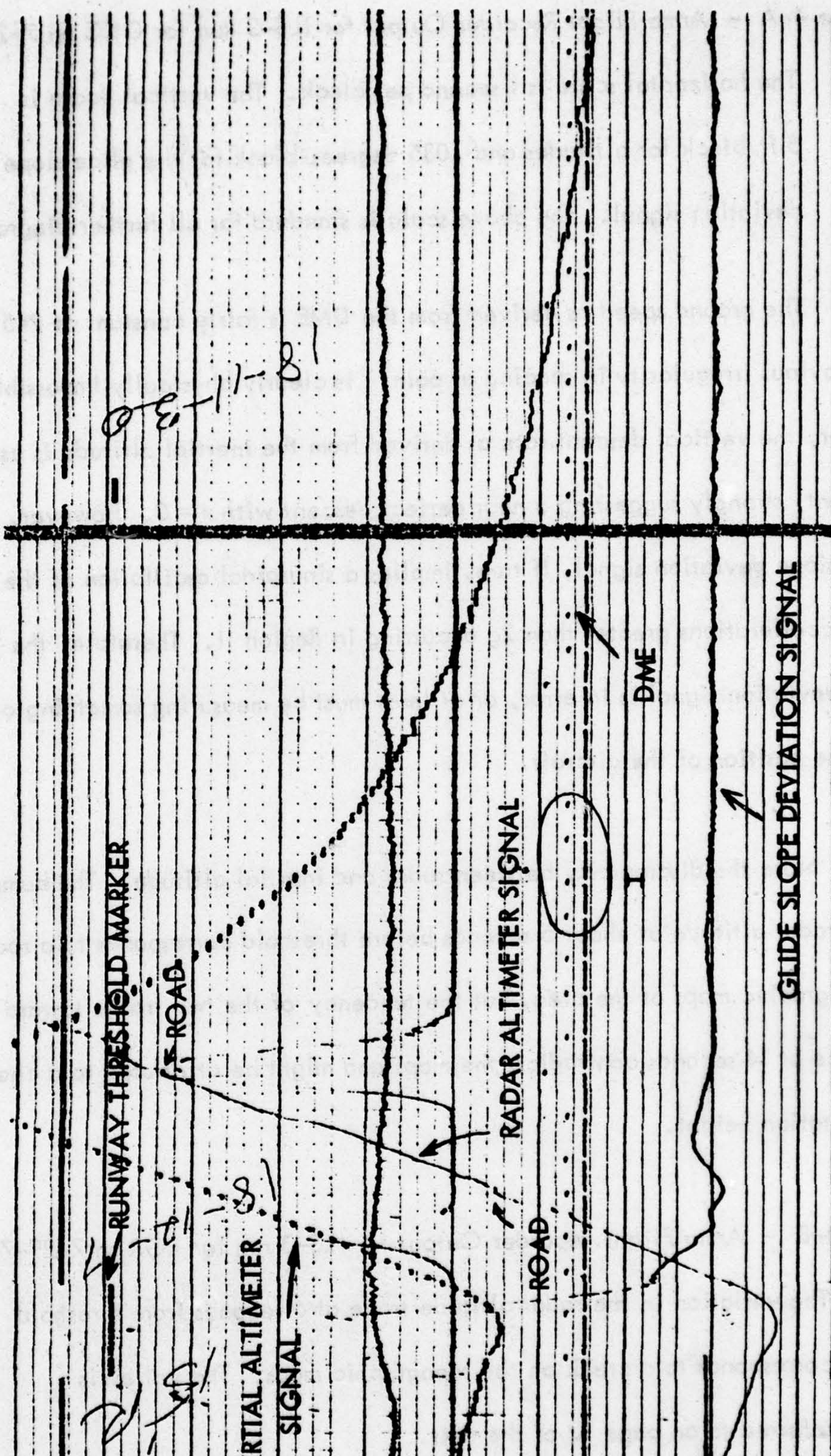

RUNWAY THRESHOLD MARKER
ROAD
INERTIAL ALTIMETER SIGNAL
RADAR ALTIMETER SIGNAL
ROAD
DME
GLIDE SLOPE DEVIATION SIGNAL

FIGURE 4-D

Figure 4-A - Arma Flight Recorder Output for ILS-3 Run for OKC on 7-28-77

The horizontal scale is 1 second per block. The vertical scale is 5 ft/block for altitudes and .035 degrees/block for the glide slope deviation signal. The above scale is standard for all further diagrams.

The ground speed as derived from the DME is fairly constant at 245 ft/sec. The obvious irregularity in spacing at point I is clearly physically impossible. Further, the vertical descent rate as derived from the inertial altitude is essentially constant, strongly suggesting a near perfect descent with $\delta = 0$. However, the glide slope deviation signal, if true, implies a sinusoidal oscillation of the craft with accellerations greater than 2g occurring in Region II. Therefore, the glide slope deviation signal is in error, or at least must be measuring something other than the position of the aircraft.

Note the discrepancy between radar and inertial altitude. The bump in the radar altitude at about 5 seconds before threshold corresponds to a road on topographic maps of the area, but the tendency of the two traces toward convergence at 14 seconds contradicts the maps and might be attributed to a change in vegetation height.

Figure 4-B - Arma Flight Recorder Output for ILS-3 run for RGR on 7-29-77

The variation in the radar altitude trace at 6 seconds from threshold corresponds to a creek on the topographic maps. The valley is referred to on page 13 of the text.

Figure 4-C - Arma Flight Recorder Output for ILS-3 run for PVO on 11/11/77

This run was made under turbulent conditions as indicated by the variations in the glide slope deviation trace. Modeling the trace in Region I as a sine wave of period 12 seconds, we can estimate that a vertical accelleration as great as .2g was encountered.

Figure 4-D - Arma Flight Recorder Output for ILS-3 run for PVO on 11/11/77

The flight conditions were now calm as evidenced by the glide slope and constant descent rate. Note however, the variations on the radar altimeter. The notches in the trace correspond well with roads, but the other features can only be vegetation which does not show up on topographic maps. Note the uneven spacing of the DME output in Region I.

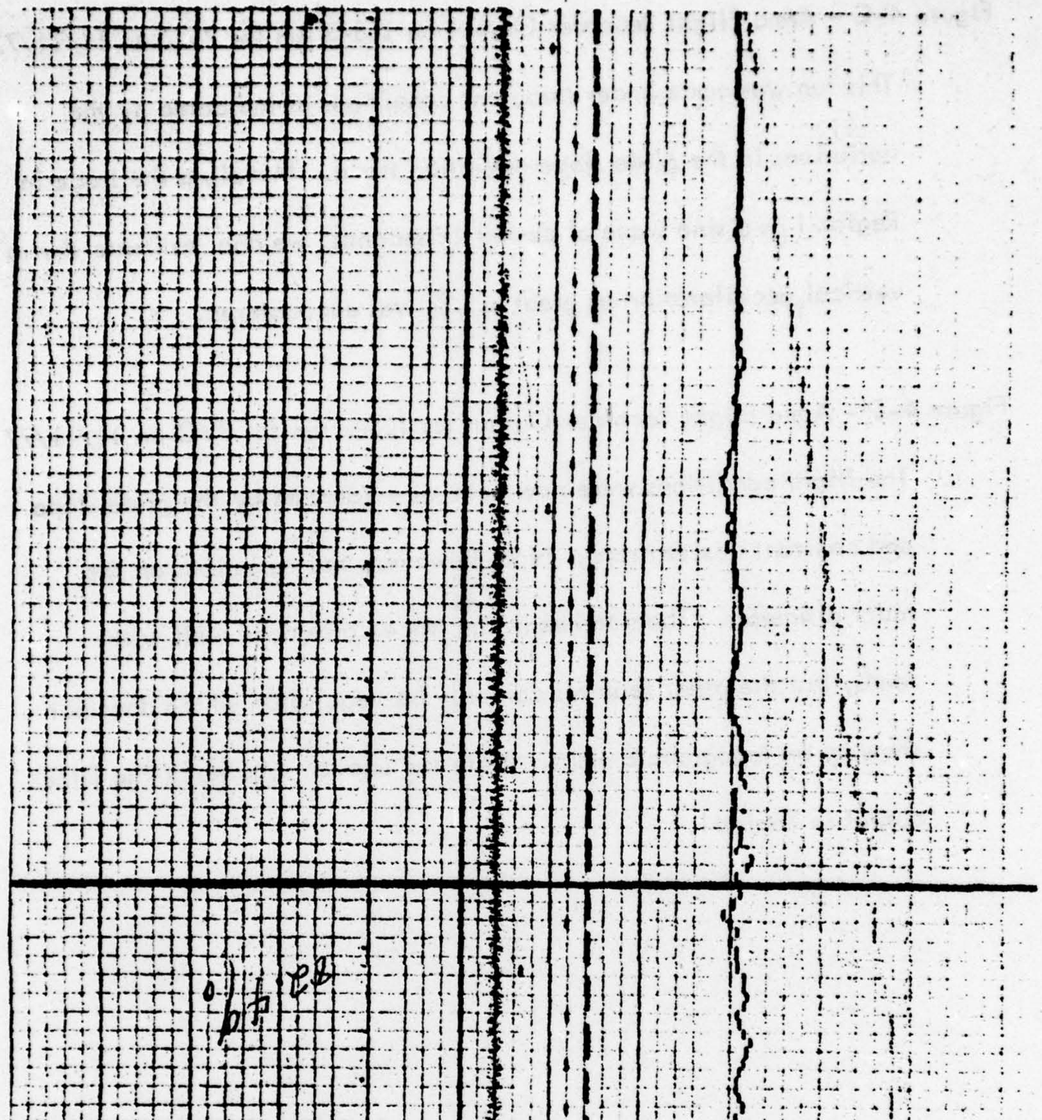


FIGURE 5-A

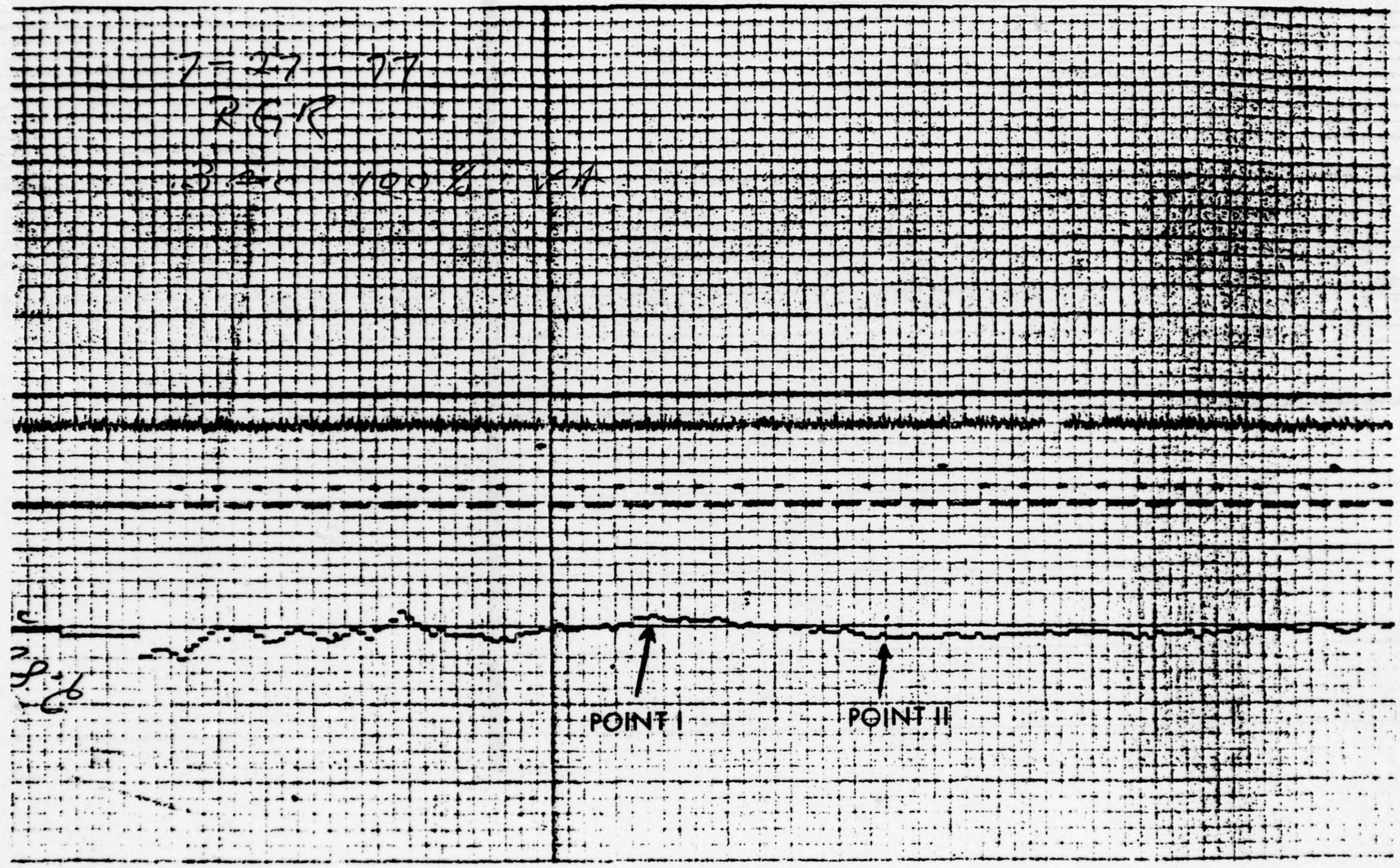



FIGURE 5-B

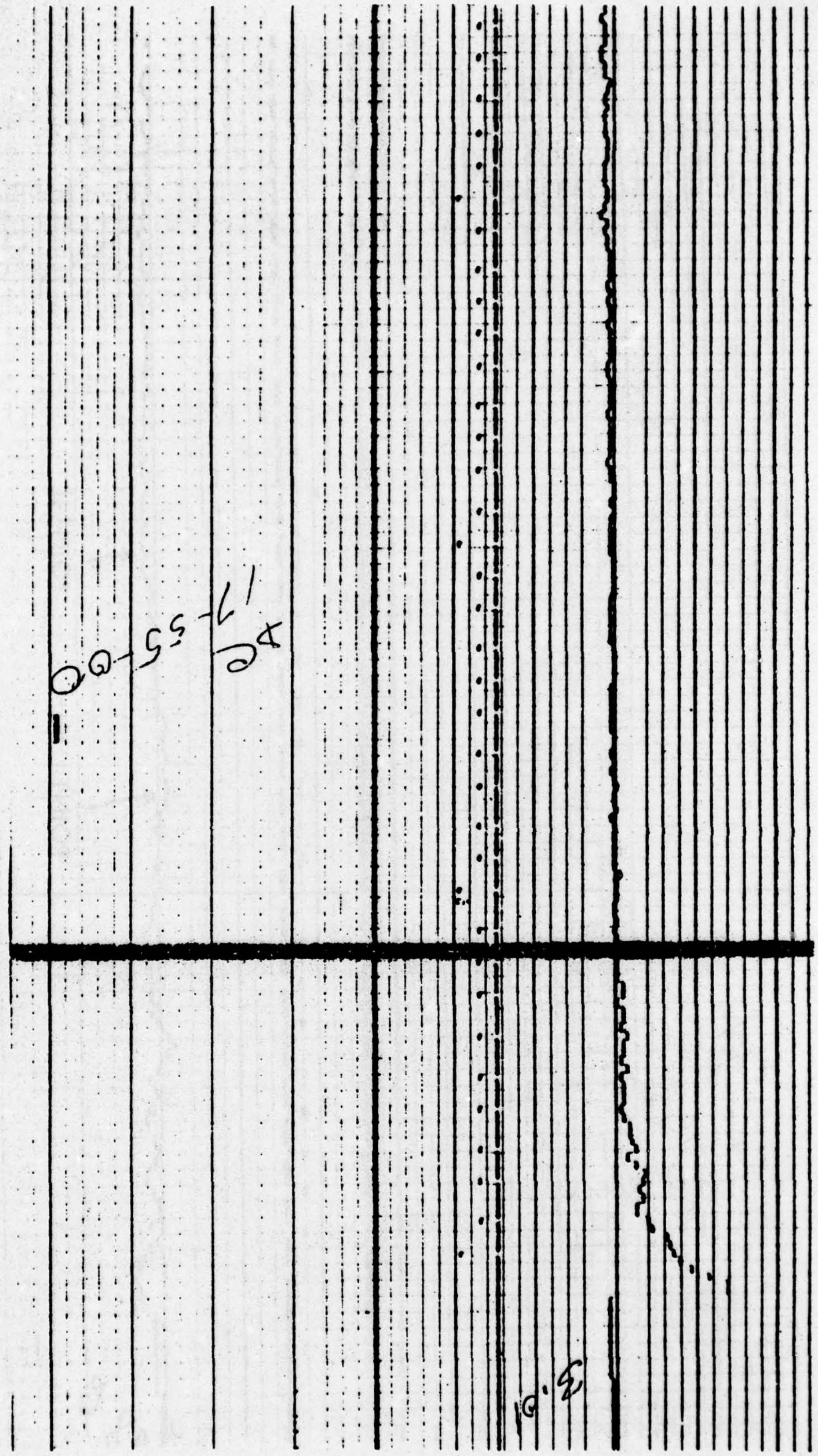



FIGURE 5-C

Figure 5-A - Arma Flight Recorder Glide Slope Structure ( $\delta_s$ ) Output for OKC

For this and all further plots of $\delta_s$ the vertical scale is .05 degree/line and the horizontal scale is 1 sec/line or approximately 245 ft/sec.

Figure 5-B - Arma Flight Recorder Glide Slope Structure ( $\delta_s$ ) Output for RGR

Points I and II refer to page 10 of the text.

Figure 5-C - Arma Flight Recorder Glide Slope Structure ( $\delta_s$ ) Output for PVO

This is an exceptionally structureless glide slope. The hyperbolic variation near threshold results from an error in the position fix.

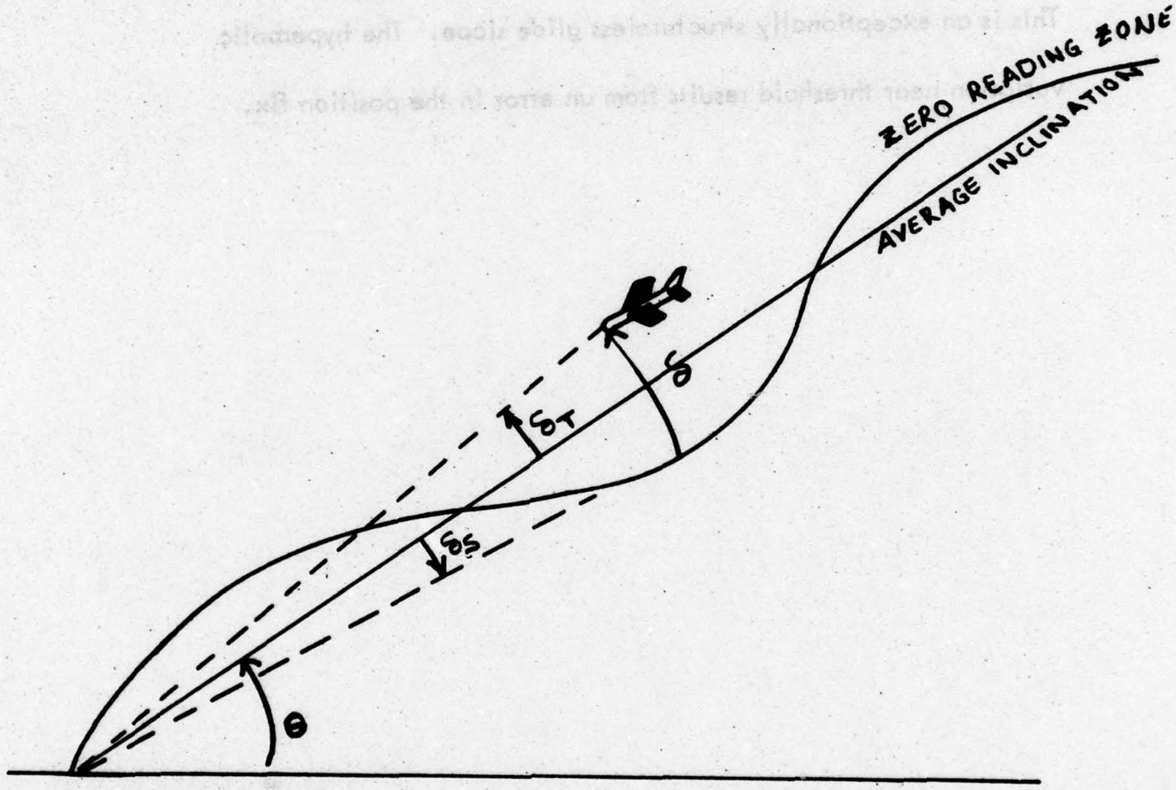



FIGURE 6

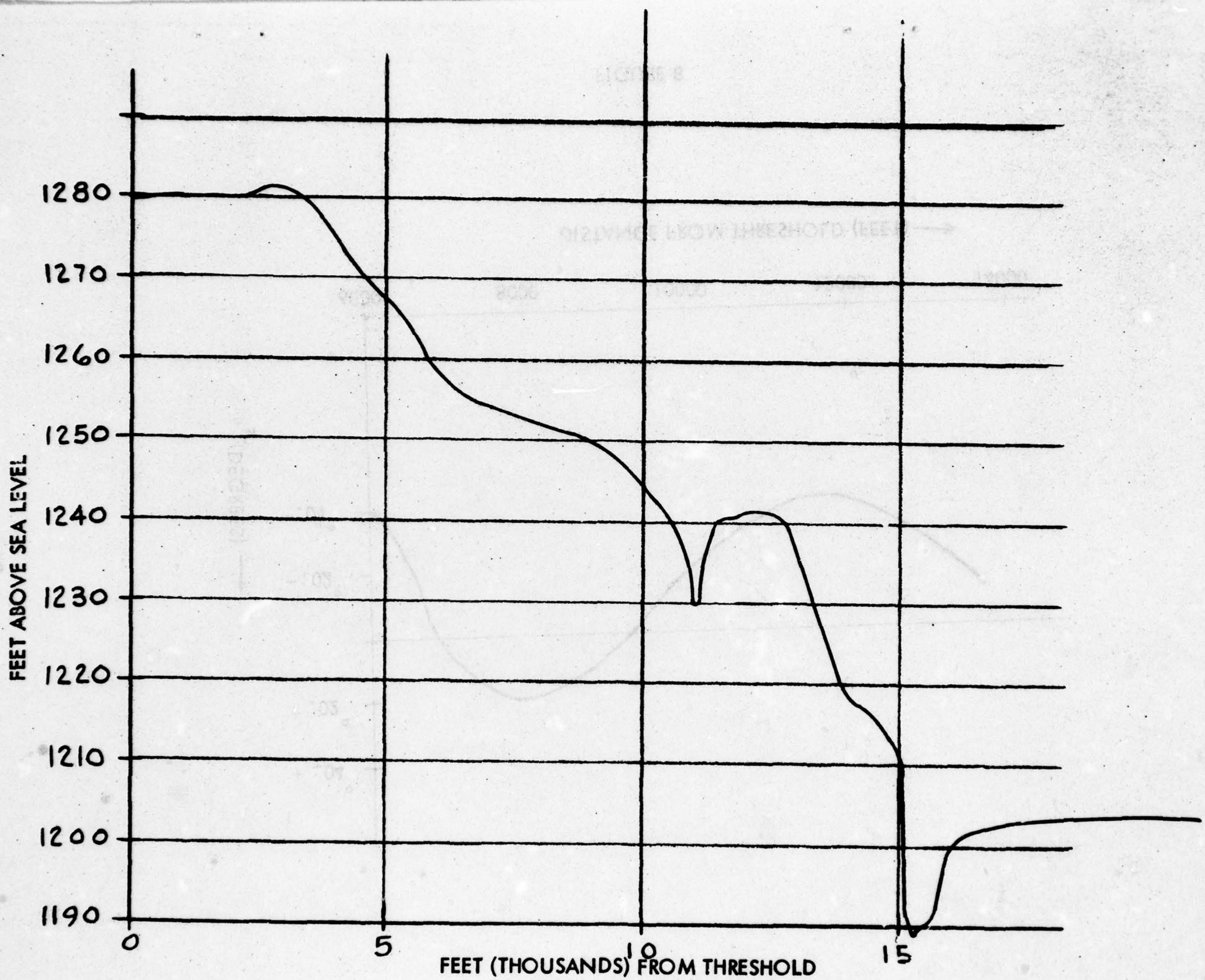

FEET ABOVE SEA LEVEL
1280
1270
1260
1250
1240
1230
1220
1210
1200
1190
0
5
10
15
FEET (THOUSANDS) FROM THRESHOLD

FIGURE 7

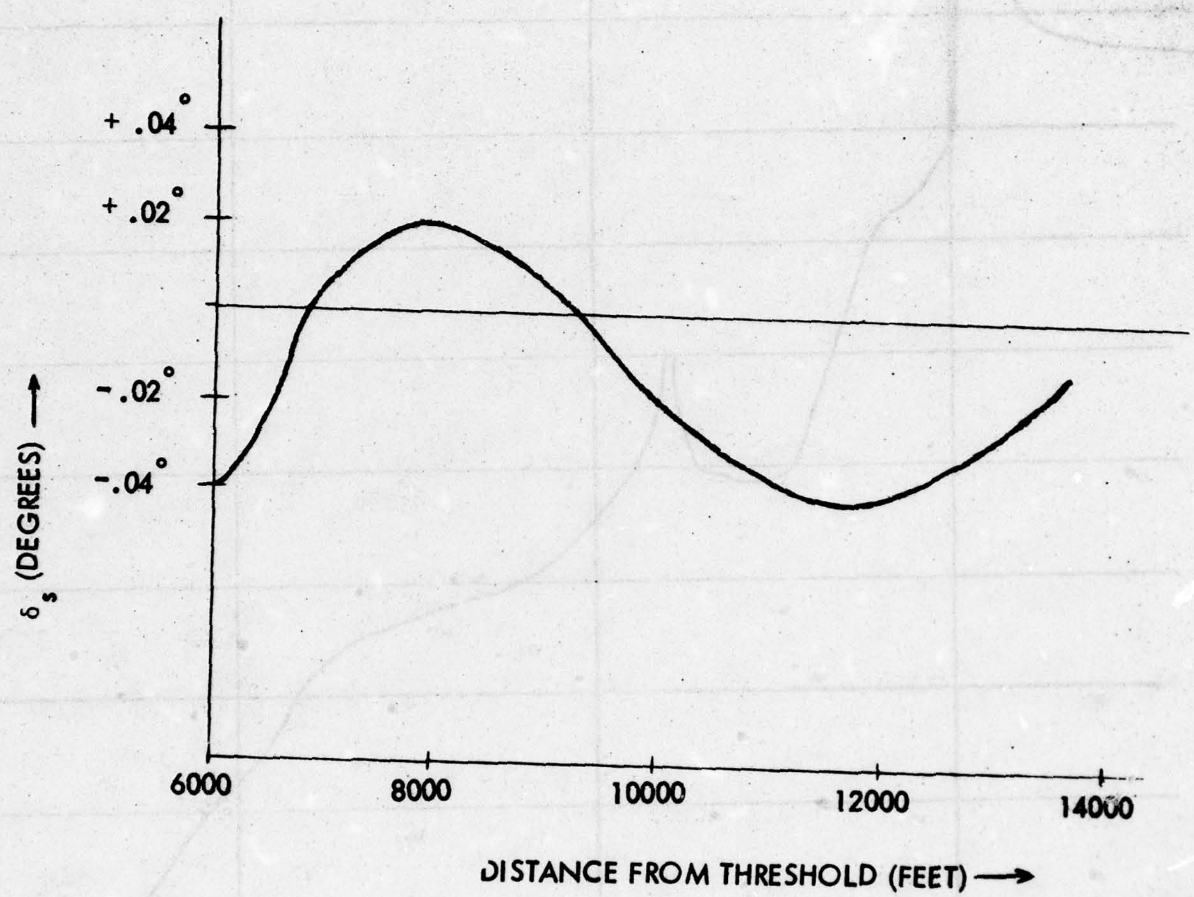

+ .04°
+ .02°
-.02°
-.04°
$\delta_s$ (DEGREES) →
6000
8000
10000
12000
14000
DISTANCE FROM THRESHOLD (FEET) →

FIGURE 8

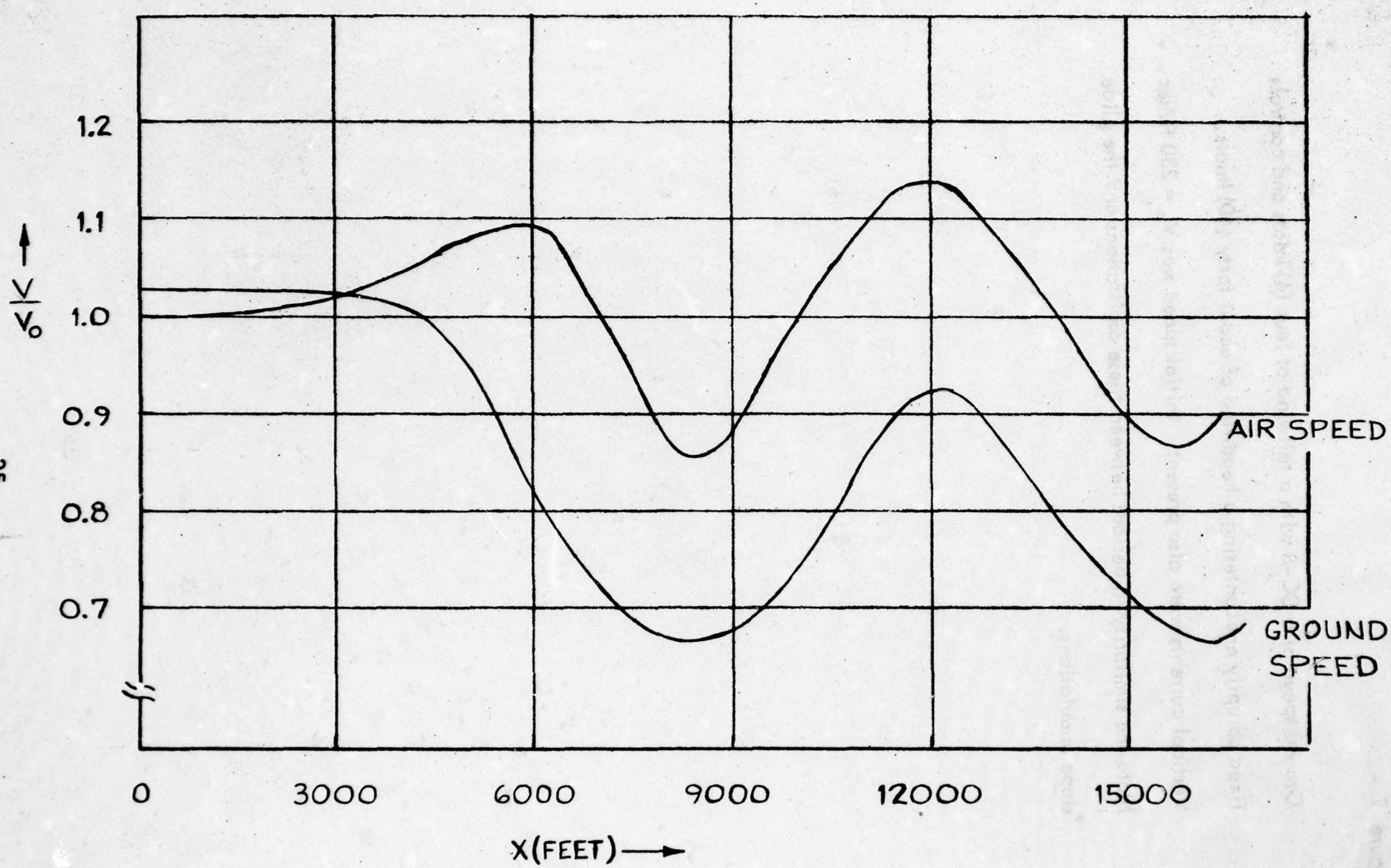

1.2
1.1
1.0
0.9
0.8
0.7
V/V₀
0
3000
6000
9000
12000
15000
X(FEET)
AIR SPEED
GROUND SPEED

FIGURE 9

Figure 9 -

Ground speed of a DC-8 with a tailwind of four (4) knots and controls fixed abruptly encountering a headwind of about forty (40) knots. Vertical currents were also present. Initial speed was $V_o$ = 230 ft/sec. Note the similarity in periods between these oscillations and the glide slope undulations.

## REFERENCES


1. Gartner W.B., et al., "Piloted Flight Simulation Study of Low-Level Wind Shear, Phase 2," Report No. FAA-RD-77-157, Federal Aviation Administration, p. 111, March 1977.

2. Kayton M., "Landing Guidance," in M. Kayton and W. Fried (eds.), Avionics Navigation Systems, John Wiley & Sons, New York, 1969, p. 532.

3. "Flight Inspection System," Arma Document No. FI-ED-147, p. 19, May 12, 1977.

4. Kayton M., "Landing Guidance," in M. Kayton and W. Fried (eds.), Avionics Navigation Systems, John Wiley & Sons, New York, 1969, p. 533.

5. Frost F., and Crosby B., "Investigations of Simulated Aircraft Flight Through Thunderstorm Outflows," NASA Contractor Report 3052, pp. 30, 41, September 1978.

6. Greene G., et al., "Wind Shear Characterization," Report No. FAA-RD-77-33, Federal Aviation Administration, p. 85, February 1977.